Particle dynamics in strong electromagnetic fields

Presented by Johann Rafelski

THE UNIVERSITY OF ARIZONA

Zimányi School Winter Workshop
On heavy Ion Collisions
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Research Group at Tucson, Arizona

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3. **Chris Grayson**
4. **Will Price**
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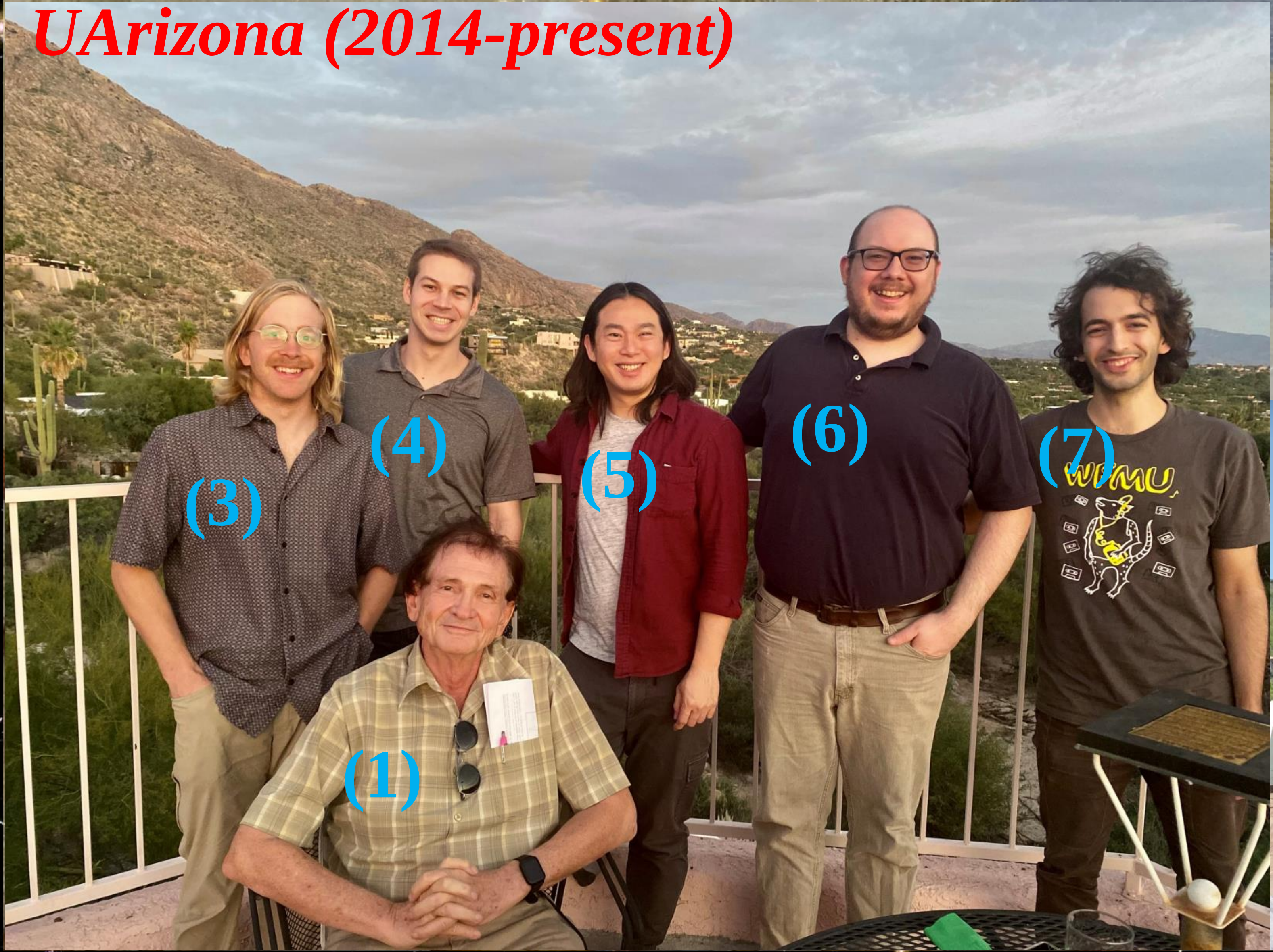
6. **Andrew Steinmetz**
7. **Stefan Evans**



Part 1: Plasmas in the Universe

Quark-gluon plasma (QGP) *probed in heavy-ion collisions*

Hadronic plasmas

e^+e^- and neutrino plasmas

Part 2: From Plasma Physics to Laws of Physics

Classical & quantum magnetization

Matter in laser fields

Radiation reaction

Temperature & acceleration

The Entire Universe… today.

Everything according to ΛCDM

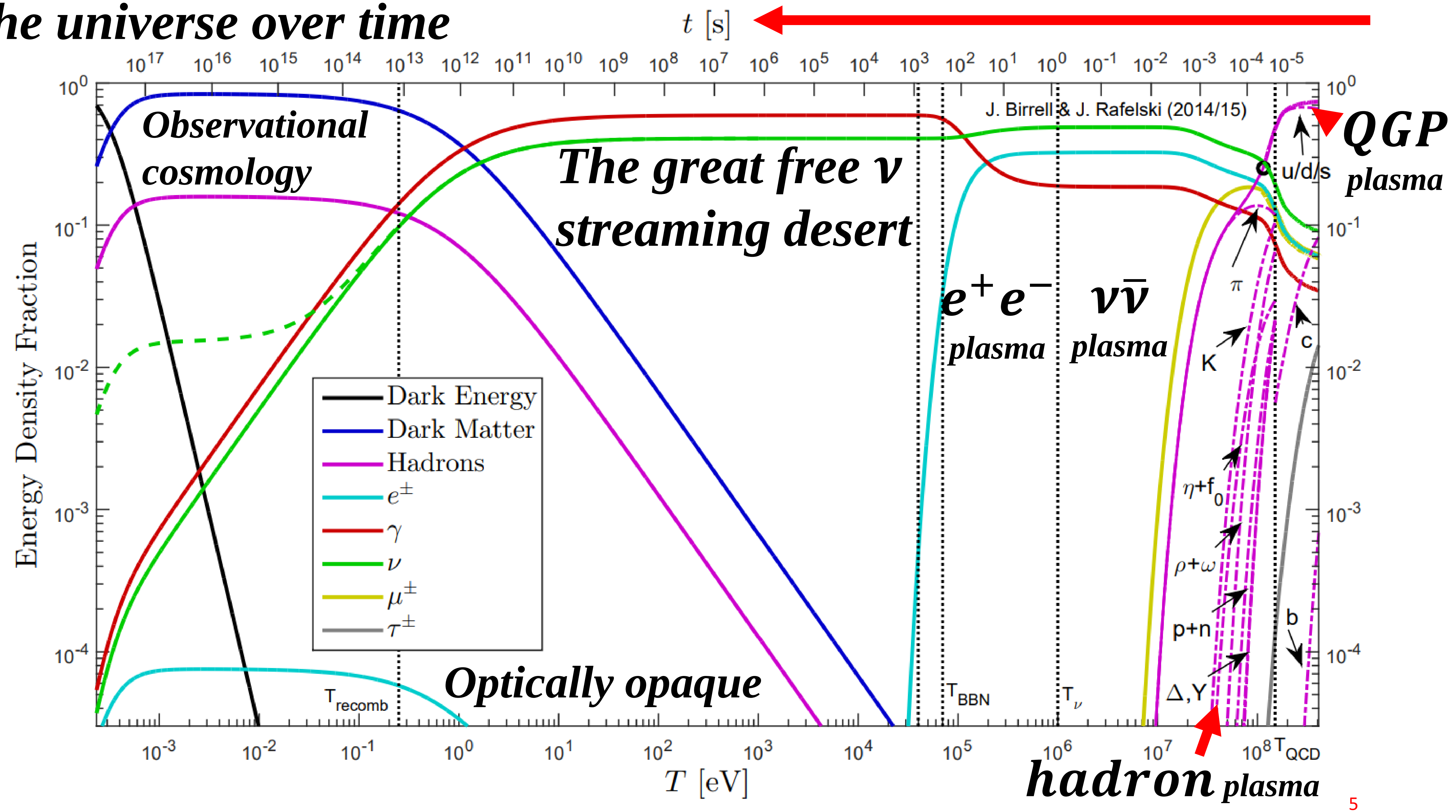
- Radiation (≪ 1%)
- Matter
  - Visible Matter (4.9%)
  - Dark Matter (26.5%)
  - Relics (≪ 1%)
- Dark Energy (68.5%)

Where is the plasma hiding? In time.

Image Credit: NASA, ESA, S. Beckwith (STScI) and the HUDF Team

M. Tanabashi et al. (Particle Data Group), "Review of Particle Physics" Phys. Rev. D 98, 030001 (2018)

The universe over time



Part 1: Plasmas in the Universe
From QGP to BBN

We use strong fields in heavy-ion collisions to probe QGP which existed from the Big Bang to when the universe was only 25 microseconds old.

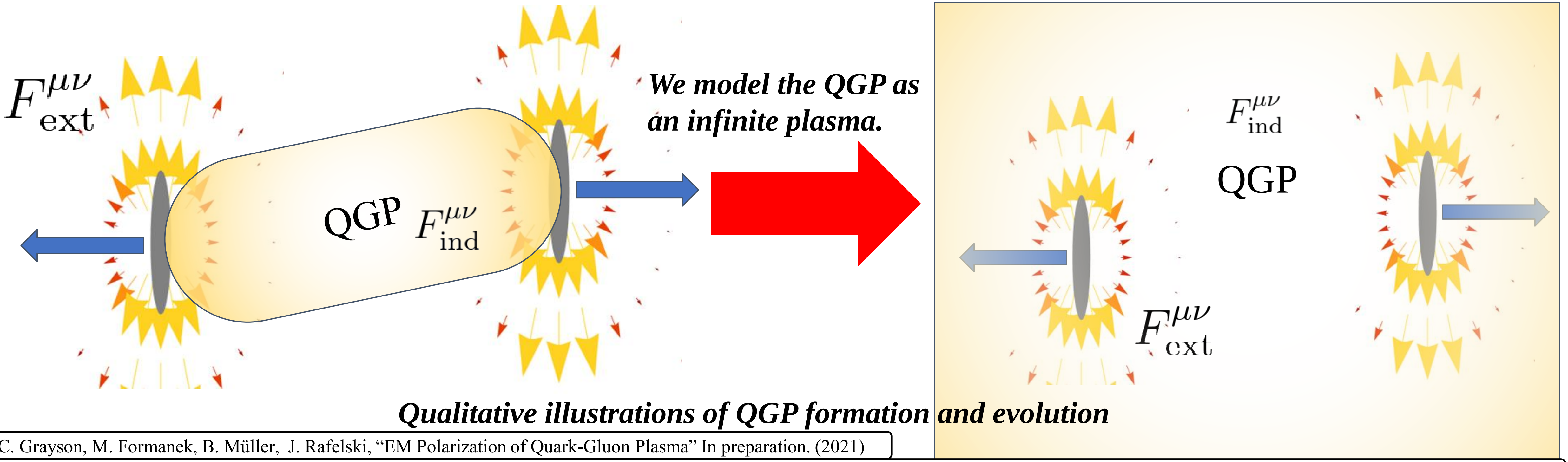
- **Primordial QGP** ($130\ \mathrm{GeV} > T > 150\ \mathrm{MeV}$)
  At this point deconfined quarks, leptons, gauge mesons freely propagating.
- **Hadronic plasma** ($150\ \mathrm{MeV} > T > 10\ \mathrm{MeV}$)
  Hadronization occurs around $T_h \approx 150\ \mathrm{MeV}$ converting free quarks into confined states.
- **Neutrino plasma** ($10\ \mathrm{MeV} > T > 1\ \mathrm{MeV}$)
  Dense plasma of electrons, positrons, and neutrinos still coupled to the charged leptons.
- $\boldsymbol{e^+e^-}$ **plasma** ($1\ \mathrm{MeV} > T > \sim 0.02\ \mathrm{MeV}$)
  Neutrino freezeout occurs around $T_\nu \approx 1\ \mathrm{MeV}$ leaving the plasma only now electrons and positrons. **Big Bang Nucleosynthesis (BBN) occurs within this plasma.**

Quark-gluon plasma (QGP)
probed in heavy-ion collisions

Ultra-strong electromagnetic fields in heavy-ion collisions:

- Combined self consistent ion and QGP electromagnetic fields
- Probing short lived systems, EM pair production and QGP plasma

See presentation by Chris Grayson



Qualitative illustrations of QGP formation and evolution

C. Grayson, M. Formanek, B. Müller, J. Rafelski, "EM Polarization of Quark-Gluon Plasma" In preparation. (2021)

M. Formanek, C. Grayson, J. Rafelski, B. Müller, "Current-Conserving Relativistic Linear Response for Collisional Plasmas" Annals of Physics 434 (2021) doi:10.1016/j.aop.2021.168605 [arXiv:2105.07897]

K. Tuchin, "Particle production in strong electromagnetic fields in relativistic heavy-ion collisions." Advances in High Energy Physics (2013)

Quark-gluon plasma (QGP) *probed in heavy-ion collisions*
Visualization of EM fields in relativistic collisions

$$\lambda_\mu = \frac{h}{m_\mu c}$$

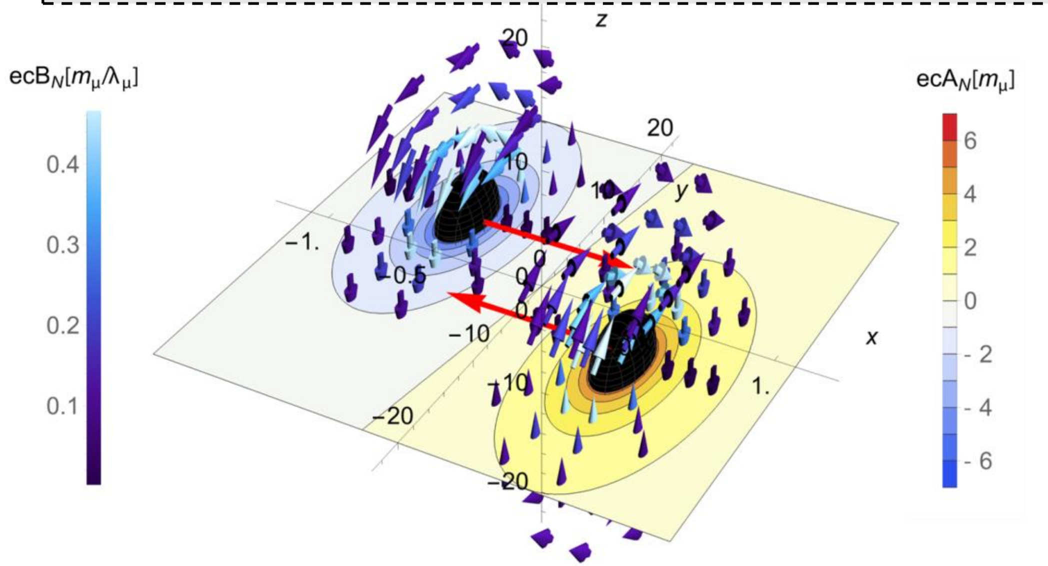
The natural EM fields $F^{\mu\nu}_{ext}$ of the ions is described used Lienard-Wiechert fields, which contains a boosted Coulomb field proportional to velocity and an acceleration or radiation field.

All questions to Chris Grayson

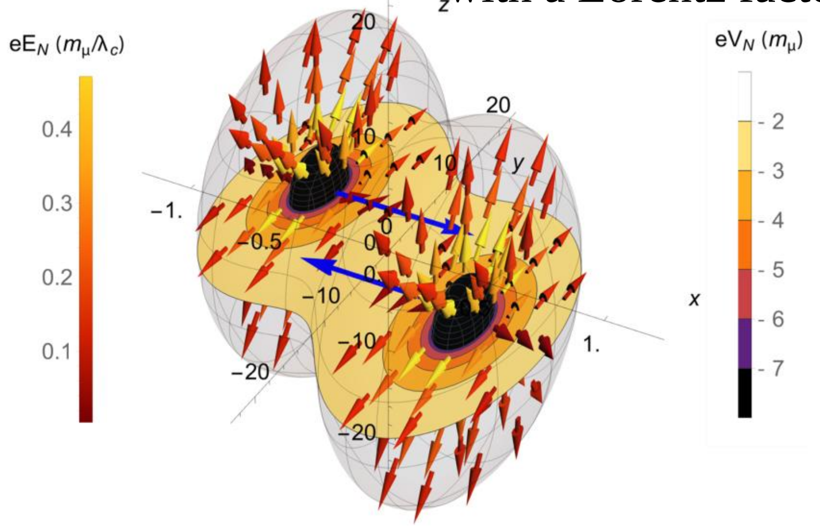
$$e\boldsymbol{E}(\boldsymbol{r},t) = Z\alpha\hbar c\left(\frac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^3|\boldsymbol{r}-\boldsymbol{r_s}|^2} + \frac{\boldsymbol{n}\times\left((\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right)}{c(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^3|\boldsymbol{r}-\boldsymbol{r_s}|}\right)_{t_r}$$

Velocity Field — *Acceleration Field*

Ions in the center-of-momentum frame are truly relativistic pancakes.
Here, we are simulating Pb-Pb collisions with a Lorentz factor of $\gamma = 37$.

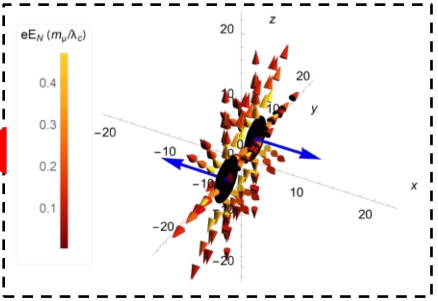


Magnetic Field



Electric Field

Original scale




Quark-gluon plasma (QGP)
probed in heavy-ion collisions

Scattering damping: κ
Medium 4-velocity: u
Distribution function: f_{eq}

$$\frac{m_\pi^2 c^2}{e\hbar} \approx 3.1 \times 10^{14}\ \mathrm{T}$$

The induced EM fields $F_{ind}^{\mu\nu}$ generated by QGP can be modelled using the Vlasov-Boltzmann equation with scattering term.

See presentation by Martin Formanek

$$(p\cdot\partial)f(x,p) + qF_{ext}^{\mu\nu}p_\nu\left(\frac{\partial f(x,p)}{\partial p^\mu}\right) = \kappa(p\cdot u)\left(f_{eq}(p)\frac{n(x)}{n_{eq}} - f(x,p)\right)$$

The induced 4-current $J_{ind}^\mu(k)$, in Fourier modes, is then

$$\tilde{J}_{ind}^\mu(k) = 2N_c\int\frac{d^4p}{(2\pi)^4}4\pi\delta_+(p^2-m^2)p^\mu\sum_{u,d,s}q_f\left(\tilde{f}_f(k,p)-\tilde{f}_{\bar{f}}(k,p)\right)$$

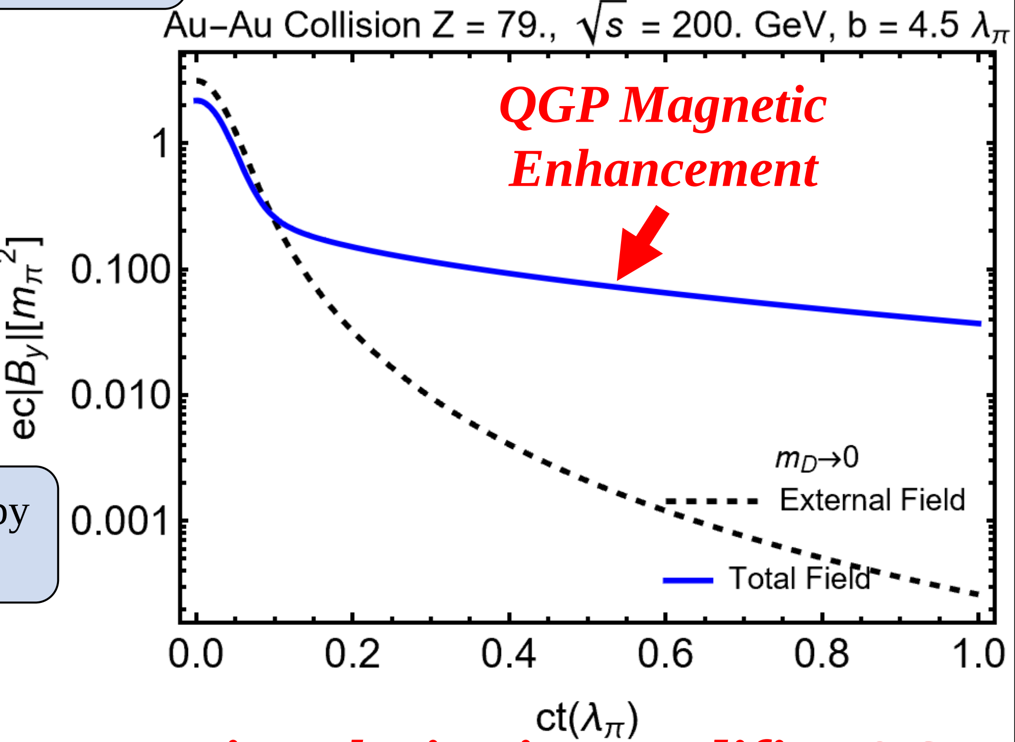
See presentation by Chris Grayson

The polarization can then be identified

$$j_i = \sigma_{ij}E_j$$

Relativistic Ohm's Law in QGP

$$\tilde{J}_{ind}^\mu(k) = \Pi_\nu^\mu\tilde{A}^\nu(k)$$



Strong electromagnetic polarization modifies QGP

C. Grayson, M. Formanek, B. Müller, J. Rafelski, "EM Polarization of Quark-Gluon Plasma" In preparation. (2021)

M. Formanek, C. Grayson, J. Rafelski, B. Müller, "Current-Conserving Relativistic Linear Response for Collisional Plasmas" Annals of Physics 434 (2021) doi:10.1016/j.aop.2021.168605 [arXiv:2105.07897]

K. Tuchin, "Particle production in strong electromagnetic fields in relativistic heavy-ion collisions." Advances in High Energy Physics (2013)

J. L. Anderson, and H. R. Witting. "A relativistic relaxation-time model for the Boltzmann equation." Physica 74.3 (1974)

Hadronic plasma: Strangeness abundance

Strangeness persists in plasma

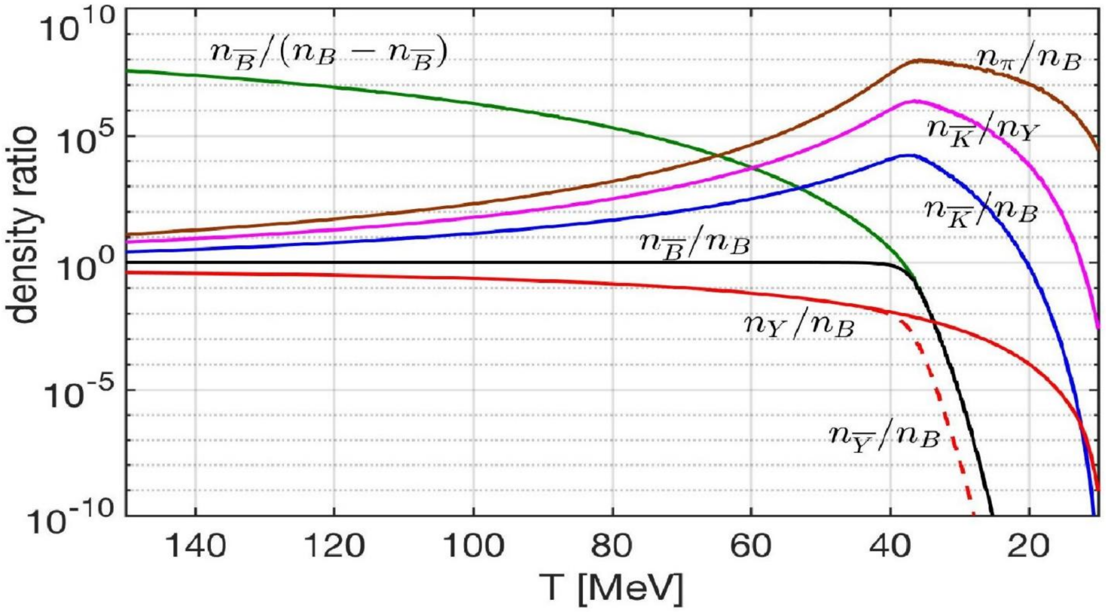


Figure 3: Ratios of hadronic particle number densities as a function of temperature 150 MeV > T > 10 MeV in the early Universe with baryon B yields: pions π (brown line), kaons $K(q\bar{s})$ (blue), antibaryon $\overline{B}$ (black), hyperon Y (red) and anti-hyperons $\overline{Y}$ (dashed red). Also shown $\overline{K}/Y$(purple).

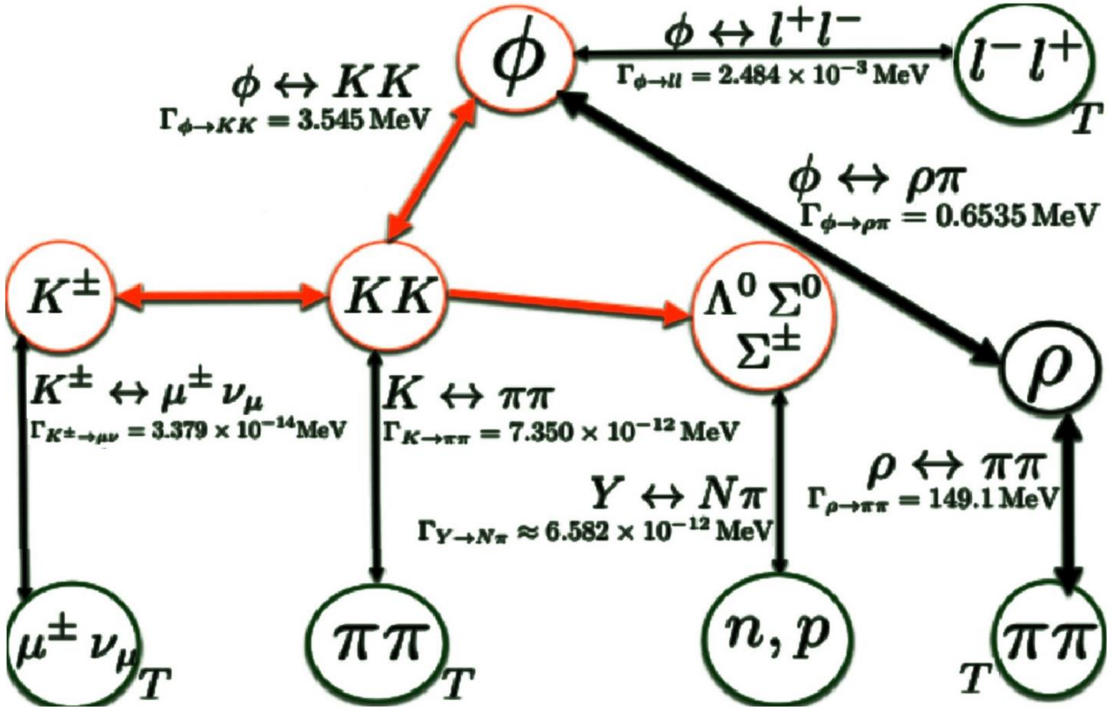
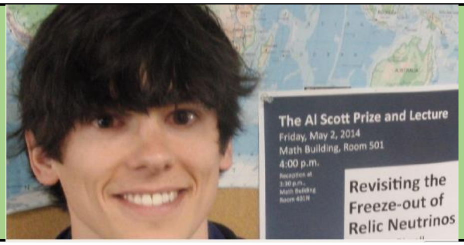


Figure 4: The strangeness abundance changing reactions in the primordial Universe. The red circles show strangeness carrying hadronic particles; red thick lines denote effectively instantaneous reactions. Black thick lines show relatively strong hadronic reactions.

C. T. Yang and J. Rafelski, “Cosmological Strangeness Abundance,” (2021) [arXiv:2108.01752]



Neutrino plasma

Neutrino freezeout occurs around $T_\nu \approx 1.5 - 2$ MeV leaving the plasma only now electrons and positrons.

J. Birrell, et al “Relic Neutrino Freeze-out: Dependence on Natural Constants,” Nucl. Phys. B **890** (2014) 481 [arXiv:1406.1759 [nucl-th]].

J. Birrell and J. Rafelski, “Quark-gluon plasma as the possible source of cosmological dark radiation,” Phys. Lett. B **741** (2015) 77 [arXiv:1404.6005 [nucl-th]].

J. Birrell, J. Wilkening and J. Rafelski, “Boltzmann Equation Solver Adapted to Emergent Chemical Non-equilibrium,” J. Comput. Phys. **281** (2014) 896 [arXiv:1403.2019 [math.NA]].

J. Birrell and J. Rafelski, “Proposal for Resonant Detection of Relic Massive Neutrinos,” Eur. Phys. J. C **75** (2015) 2, 91 [arXiv:1402.3409 [hep-ph]].

J. Rafelski and J. Birrell, “Traveling Through the Universe: Back in Time to the Quark-Gluon Plasma Era,” J. Phys. Conf. Ser. **509** (2014) 012014 [arXiv:1311.0075 [nucl-th]].

J. Birrell, et al Mod. Phys. Lett. A **28** (2013) 1350188 [arXiv:1303.2583 [astro-ph.CO]].

J. Birrell, et al Phys. Rev. D **89** (January 2014) 023008 [arXiv:1212.6943 [astro-ph.CO]].

J. Rafelski, L. Labun and J. Birrell, “Compact Ultradense Matter Impactors,” Phys. Rev. Lett. **110** (2013) 11, 111102 [arXiv:1104.4572 [astro-ph.EP]].

Skipping the era…

Early universe plasma

e^+e^- plasma

The chemical potential for the e^+e^- plasma from principle of charge neutrality:

$$n_e - n_{\bar{e}} = n_p - n_{\bar{p}} \approx n_p$$

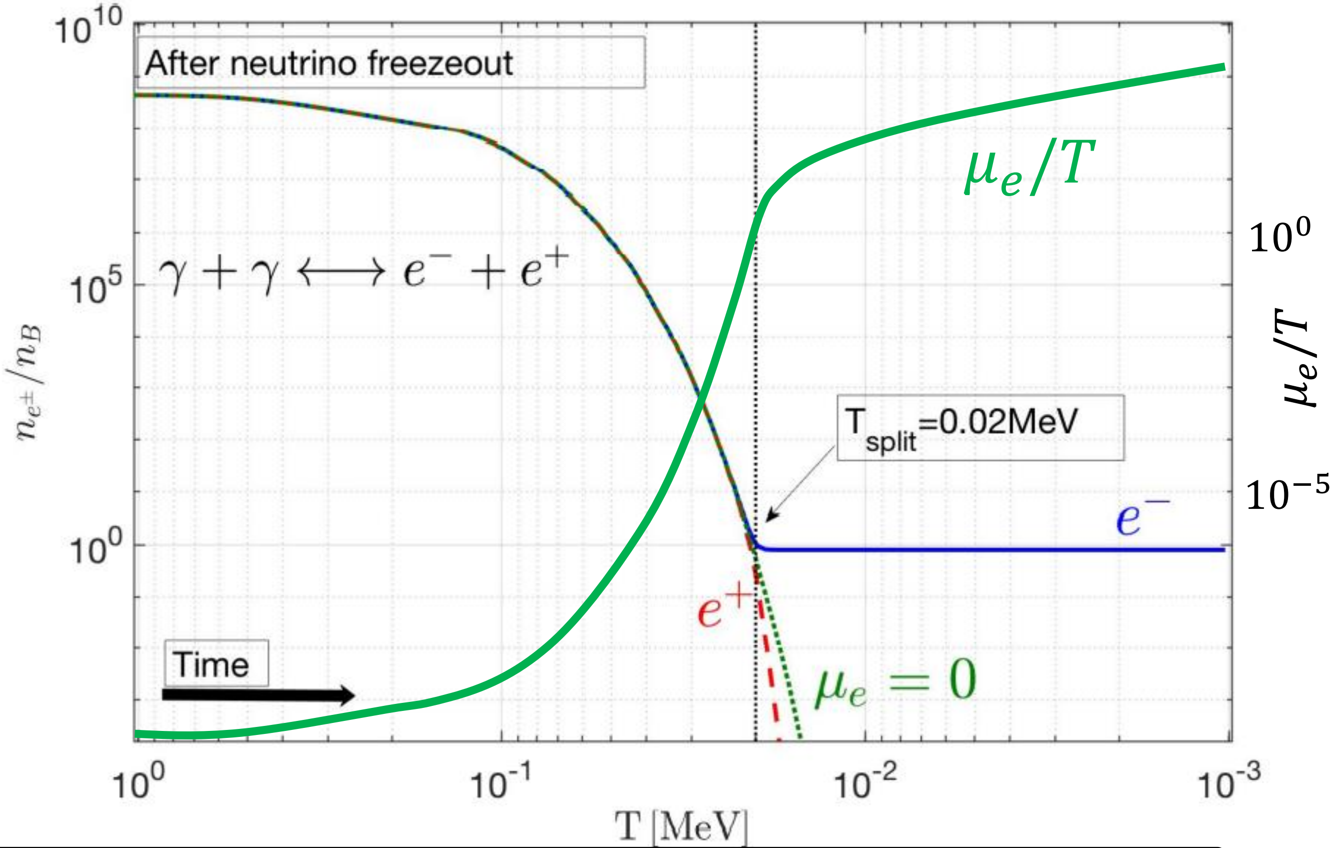
Comoving baryon number and entropy conservation. $T \leq T_f^\nu$

$$n_B/s = constant$$
$$s \propto n_\gamma = 6.2(\pm 0.4) \times 10^{-10} n_B$$

Comoving temperature in radiation dominated Universe: Neutrino example.

FLRW Scale factor

$$T_\nu(t) = T_f \frac{a(t_f)}{a(t)} \qquad T_f \cong 2\ \text{MeV}$$



M. J. Fromerth, I. Kuznetsova, L. Labun, J. Letessier, & J. Rafelski, "From Quark-Gluon Universe to Neutrino decoupling: 200< T< 2 MeV." Acta Physica Polonica B 43.12 (2012).

J. Birrell, C. T. Yang, P. Chen and J. Rafelski, "Relic neutrinos: Physically consistent treatment of effective number of neutrinos and neutrino mass," Phys. Rev. D 89, 023008 (2014) doi:10.1103/PhysRevD.89.023008 [arXiv:1212.6943]

C. Pitrou, A. Coc, J. P. Uzan and E. Vangioni, "Precision big bang nucleosynthesis with improved Helium-4 predictions" [arXiv:1801.08023], Phys. Rep. in press (2018)

B. Wang, C. A. Bertulani and A. B. Balantekin, "Electron screening and its effects on Big-Bang nucleosynthesis" Phys. Rev. C 83, 018801 (2011) doi:10.1103/PhysRevC.83.018801 [arXiv:1010.1565]

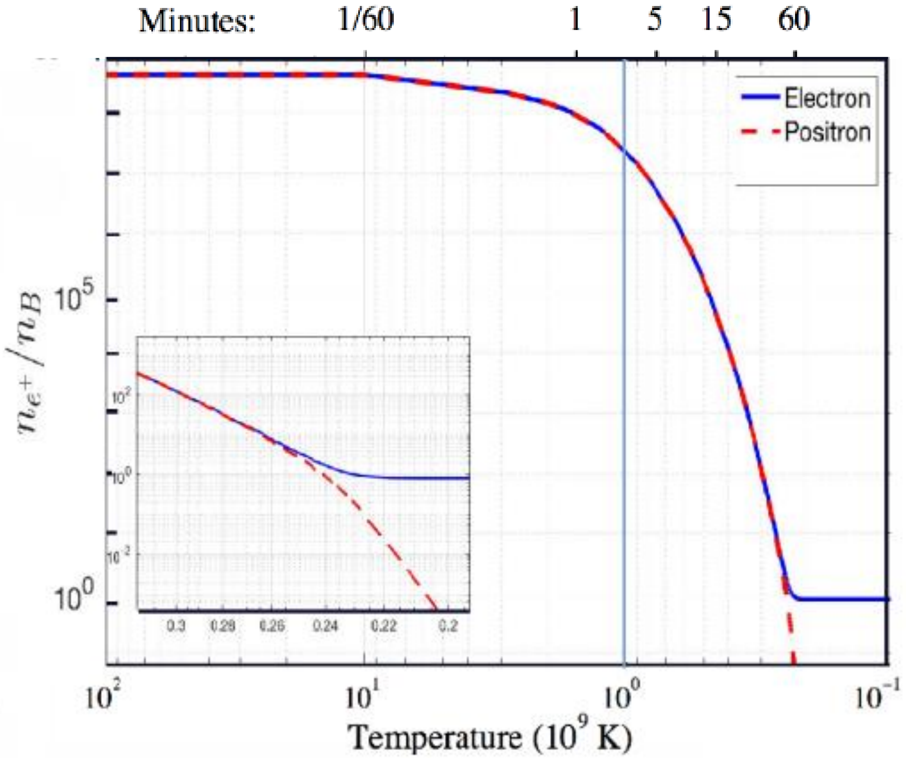
e^+e^- and BBN

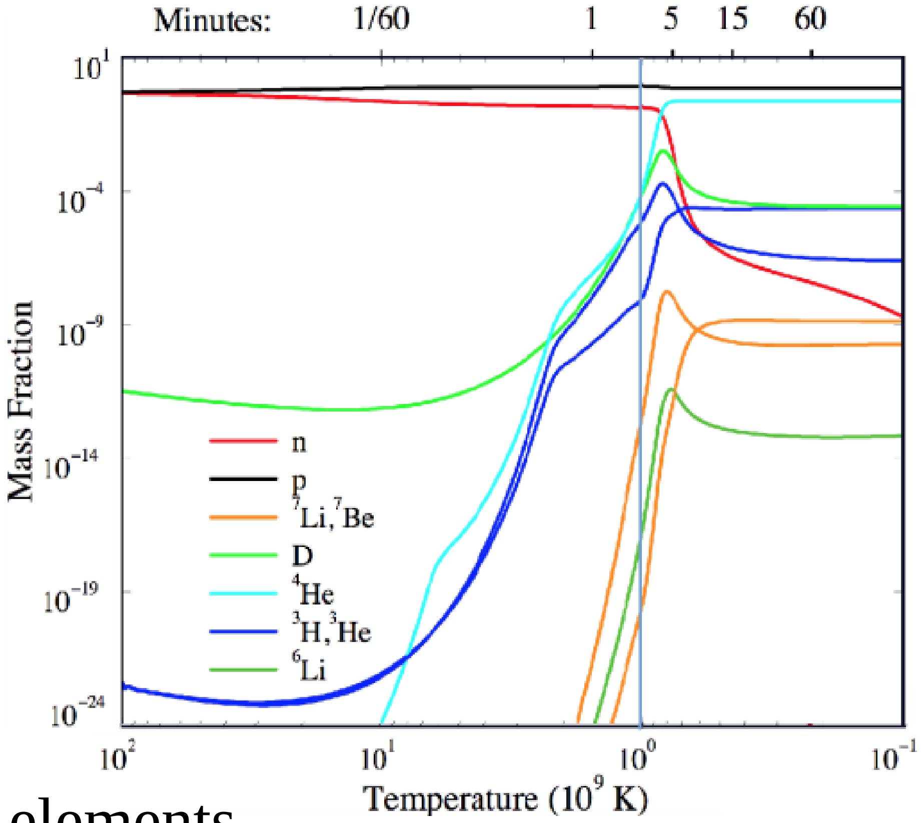
Direct overlap between the electron-positron plasma regime and BBN processes.

Big Bang Nucleosynthesis (BBN) occurs within this plasma

At $T = 0.07$ MeV we have $n_{e^\pm} \approx 10^7 n_B$

Plasma screens charges making nuclear reactions faster!





Could lead to changes in final abundance of select light elements.

C. T. Yang, J. Birrell, J. Rafelski, "Electron-Positron Plasma in Universe Expansion" In preparation.

C. Pitrou, A. Coc, J. P. Uzan and E. Vangioni, "Precision big bang nucleosynthesis with improved Helium-4 predictions" [arXiv:1801.08023], Phys. Rep. in press (2018)

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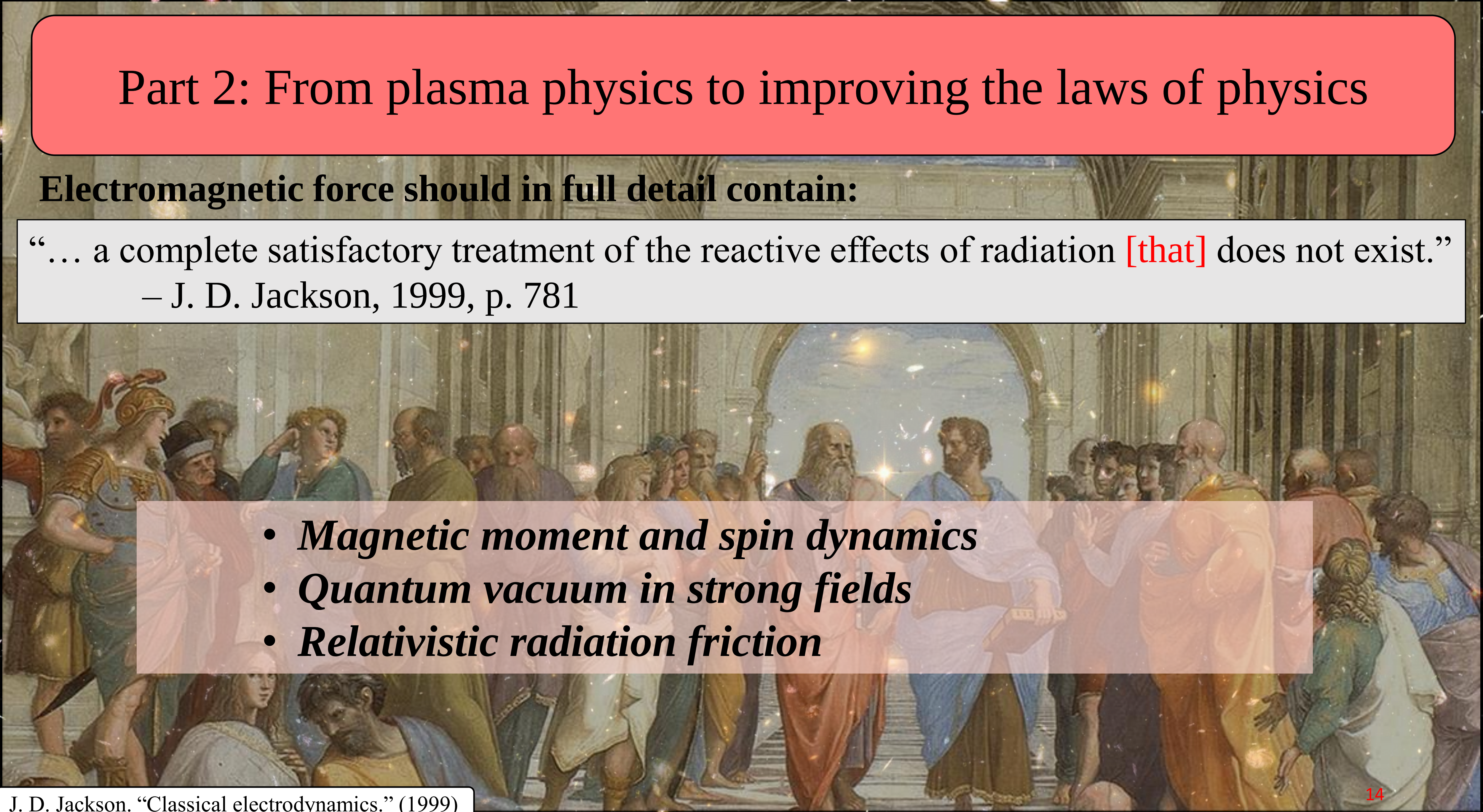


Part 2: From plasma physics to improving the laws of physics

Electromagnetic force should in full detail contain:

"… a complete satisfactory treatment of the reactive effects of radiation [that] does not exist."
– J. D. Jackson, 1999, p. 781

- ***Magnetic moment and spin dynamics***
- ***Quantum vacuum in strong fields***
- ***Relativistic radiation friction***

J. D. Jackson. "Classical electrodynamics." (1999)


Completing EM interactions: Unified covariant classical magnetic dipole interaction

Electric energy: $E_{el} = ecA^0$

Magnetic energy: $E_{mag} = d_m c B^0$ → ***Magnetic dipole charge*** $\boldsymbol{\mu} = (d_m c)\boldsymbol{S}$

A covariant magnetic potential B^μ can be introduced

$$B_\mu \equiv F^*_{\mu\nu} s^\nu = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta} s^\nu$$

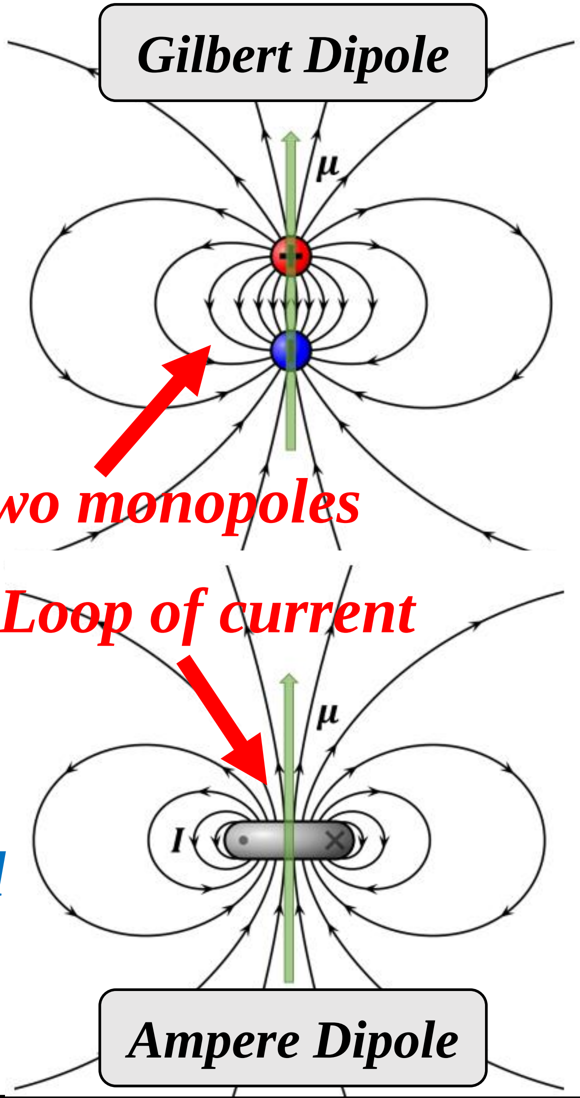
→ ***Define a Force Field Tensor***

$$G^{\mu\nu} \equiv \partial^\mu B^\nu - \partial^\nu B^\mu$$

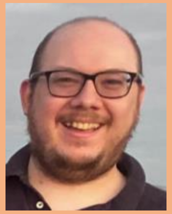
Point particle classical Lagrangian

$$L = mc\sqrt{u^2} + eA \cdot u + d_m B \cdot u$$

Covariant description contains both Gilbert and Ampere dipole structure



J. Rafelski, M. Formanek, and A. Steinmetz. "Relativistic dynamics of point magnetic moment." EPJC 78.1 (2018): 1-12.

Completing EM interactions: Unified covariant classical magnetic dipole interaction

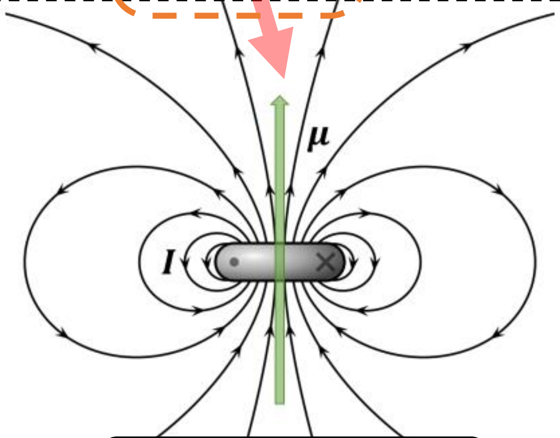
The equations of motion for the above are then

$$\dot{u}^\mu = \frac{e}{m} F^{\mu\nu} u_\nu - \frac{d_m}{m} s \cdot \partial (F^{*\mu\nu}) u_\nu - \frac{d_m}{m} \mu_0 \epsilon^{\gamma\alpha\beta\mu} j_\gamma u_\alpha s_\beta$$

We can solve this, not just academic!
(Example in supplementary material)

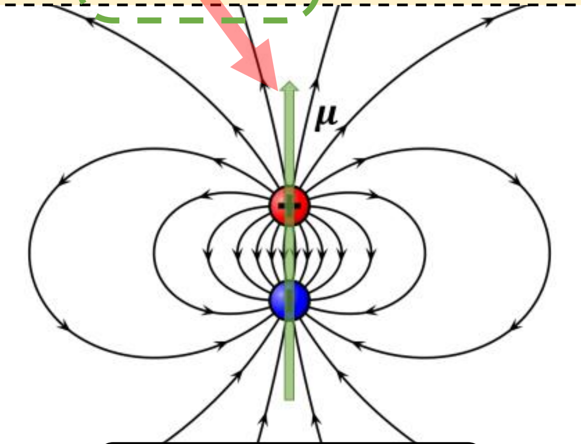
Comoving Frame (CF)

$$\boldsymbol{F}\Big|_{\mathrm{CF}} = e\boldsymbol{E} + \boldsymbol{\nabla}(\boldsymbol{\mu}\cdot\boldsymbol{B}) - \boldsymbol{\mu}\times\frac{\partial \boldsymbol{E}}{\partial t} = e\boldsymbol{E} + (\boldsymbol{\mu}\cdot\boldsymbol{\nabla})\boldsymbol{B} + \mu_0 \boldsymbol{\mu}\times\boldsymbol{j}$$



Ampere Dipole

OR



Gilbert Dipole

J. Rafelski, M. Formanek, and A. Steinmetz. "Relativistic dynamics of point magnetic moment." EPJC 78.1 (2018): 1-12.

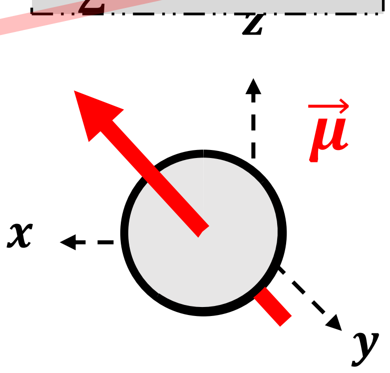
Quantum magnetic dipoles: Diverse forms of quantum equations

$$\boldsymbol{\mu} \leftarrow \frac{g}{2}\frac{e\hbar}{2m}$$

$$\frac{g}{2} = 1 + a$$

Non-relativistic magnetic dipole has the Hamiltonian:

$$\hat{H}_{Mag.} = -\vec{\boldsymbol{\mu}} \cdot \vec{\boldsymbol{B}}$$



Relativistic magnetic dipoles have a diversity of models:

$$\left(\gamma \cdot (i\hbar\partial - eA) - mc - \left(\boldsymbol{\mu} - \frac{e\hbar}{2m}\right)\frac{1}{2c}\sigma_{\alpha\beta}F^{\alpha\beta}\right)\psi = 0$$ **Dirac-Pauli (DP)**

$$\left((i\hbar\partial - eA)^2 - m^2c^2 - \boldsymbol{\mu} m\sigma_{\alpha\beta}F^{\alpha\beta}\right)\psi = 0$$ **Klein-Gordon-Pauli (KGP)**

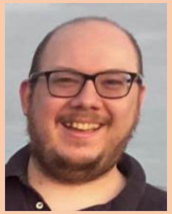
$$\left((i\hbar\partial - eA)^2 - \tilde{m}^2c^2\right)\psi = 0$$ ***"Improved" Klein-Gordon-Pauli (IKGP)***

$$\tilde{m}c = mc + \boldsymbol{\mu}\frac{1}{2c}\sigma_{\alpha\beta}F^{\alpha\beta} \rightarrow \tilde{m}^2c^2 = m^2c^2 + \boldsymbol{\mu} m\sigma_{\alpha\beta}F^{\alpha\beta} + \boldsymbol{\mu}^2\frac{1}{4c^2}\left(\sigma_{\alpha\beta}F^{\alpha\beta}\right)^2$$

A. Steinmetz, M. Formanek, and J. Rafelski. "Magnetic dipole moment in relativistic quantum mechanics." EPJA 55.3 (2019): 1-17.

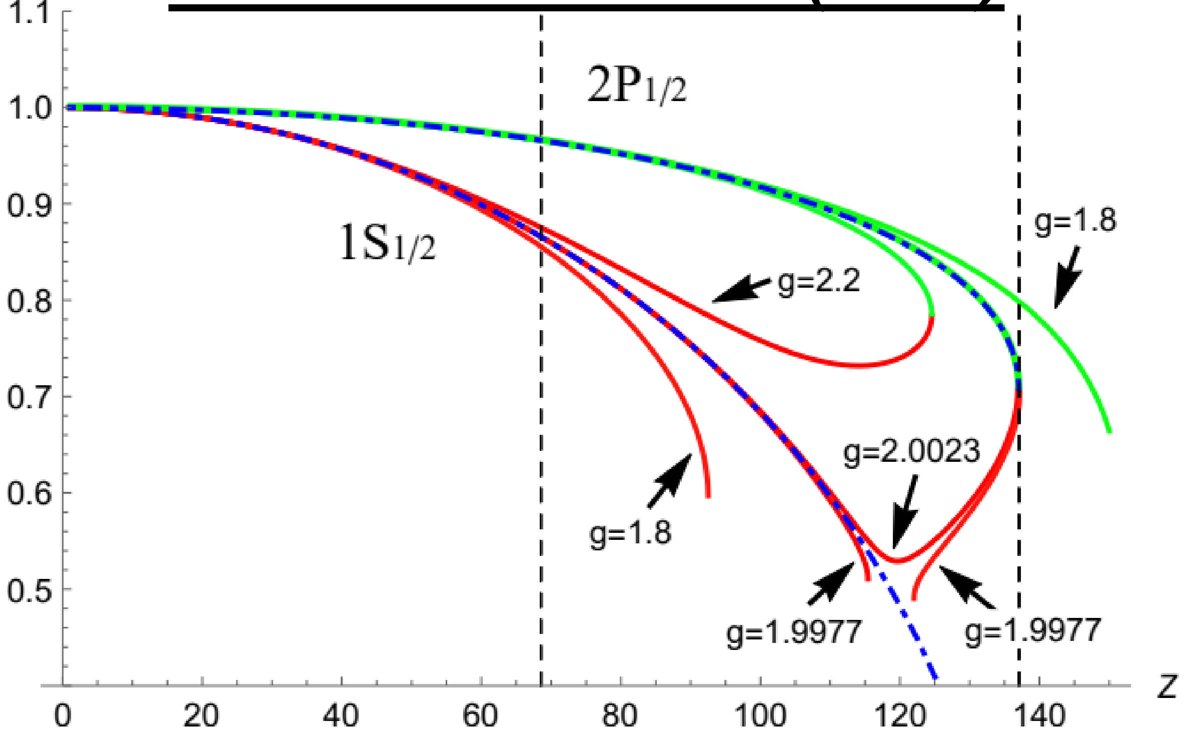
R. P. Feynman, and M. Gell-Mann. "Theory of the Fermi interaction." Physical Review 109.1 (1958)

M. Veltman, "Two component theory and electron magnetic moment," Acta Phys. Polon. B 29 (1998) 783 [hep-th/9712216]

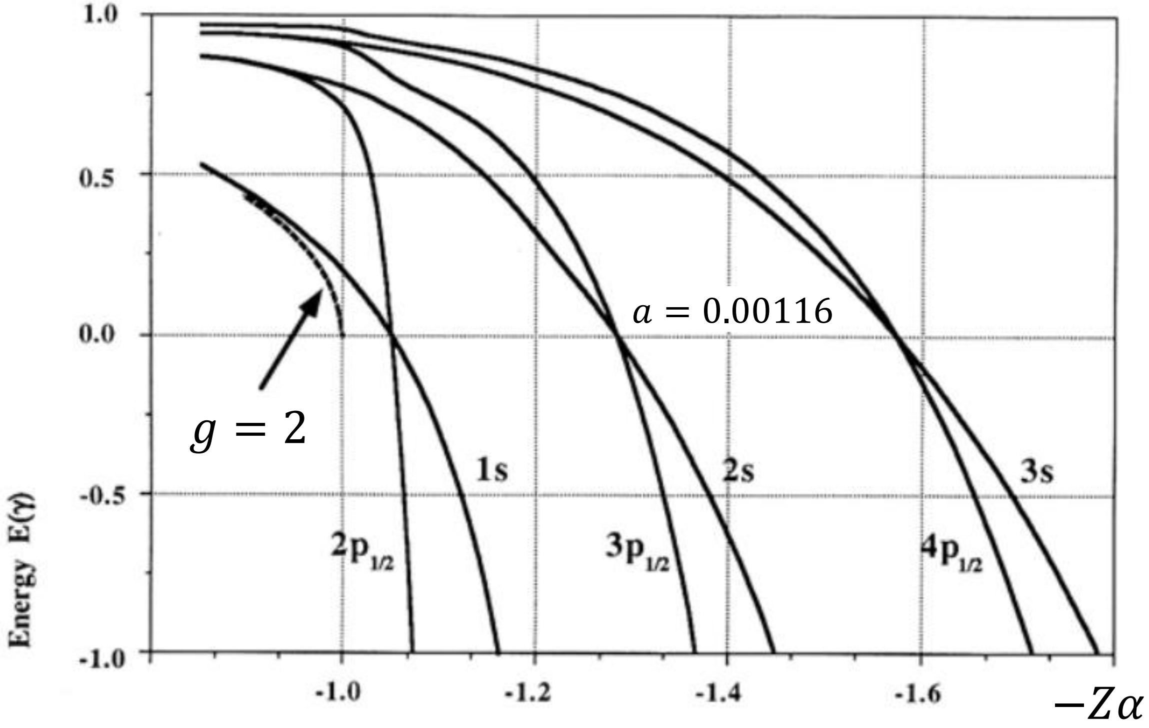


Strong Coulomb field eigen-energies

Klein-Gordon-Pauli (KGP)

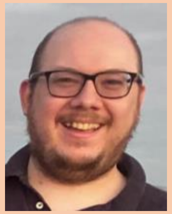


Dirac-Pauli (DP)



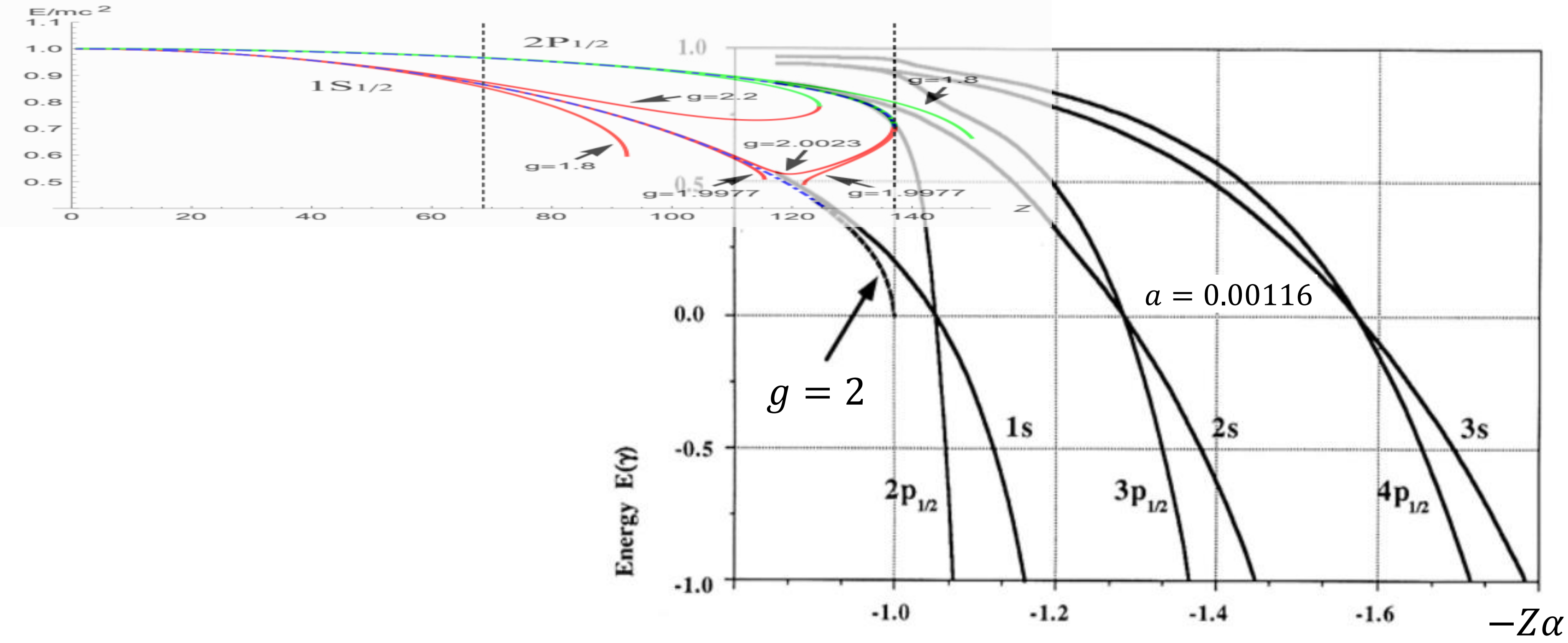
A. Steinmetz, M. Formanek, and J. Rafelski. "Magnetic dipole moment in relativistic quantum mechanics." EPJA 55.3 (2019): 1-17.

B. Thaller. The Dirac equation. Springer Science & Business Media, 2013.



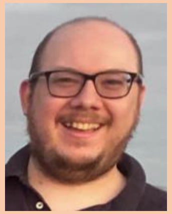
Strong Coulomb field eigen-energies

KGP and DP Spectrum with Same Scaling



A. Steinmetz, M. Formanek, and J. Rafelski. “Magnetic dipole moment in relativistic quantum mechanics.” EPJA 55.3 (2019): 1-17.

B. Thaller. The Dirac equation. Springer Science & Business Media, 2013.

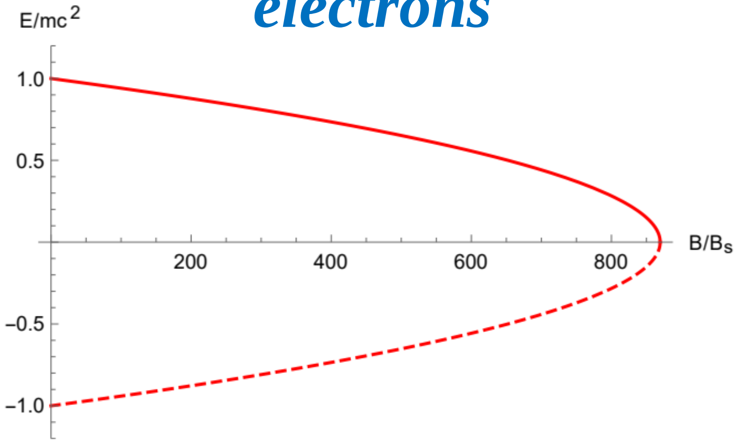


Constant magnetic field eigen-energies

$$\boldsymbol{B_S} \equiv \frac{m^2c^2}{e\hbar} = \begin{cases} 4.41 \times 10^9 \text{ T (electrons)} \\ 1.49 \times 10^{16} \text{ T (protons)} \end{cases}$$

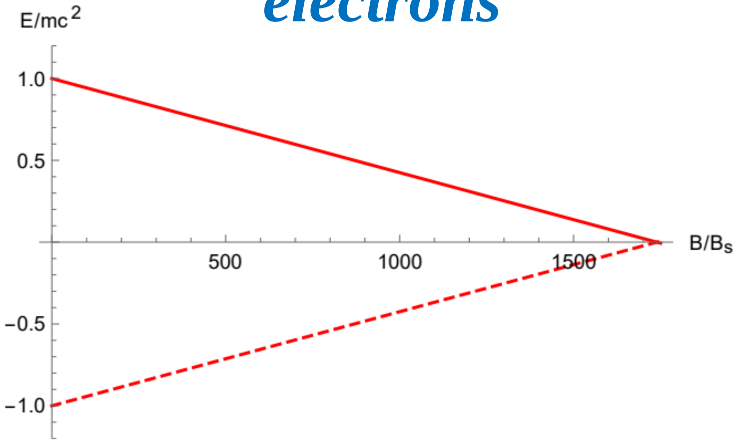
Klein-Gordon-Pauli (KGP)

electrons



Dirac-Pauli (DP)

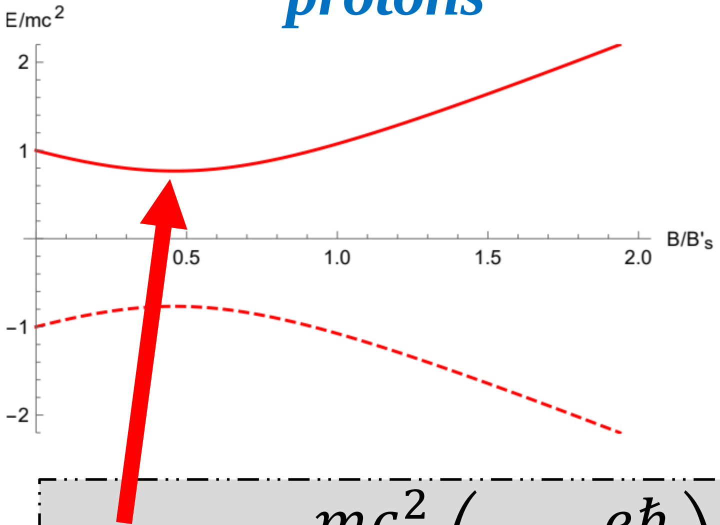
electrons



"Improved"

Klein-Gordon-Pauli (IKGP)

protons



$$\boldsymbol{B_{min}} \equiv \frac{mc^2}{\mu}\left(\mu - \frac{e\hbar}{2m}\right)$$

Expect grossly different properties in magnetars.

A. Steinmetz, M. Formanek, and J. Rafelski. "Magnetic dipole moment in relativistic quantum mechanics." EPJA 55.3 (2019): 1-17.

E. J. Ferrer, & A. Hackebill. "Thermodynamics of neutrons in a magnetic field and its implications for neutron stars" Phys. Rev. C 99.6 (2019): 065803.

QED quantum vacuum in strong fields

KGP introduces corrections into Euler-Heisenberg (**EH**) action:

- Pair production modification due to periodicity of g.

$$L_{EH} = -\frac{1}{8\pi^2}\int_{\delta}^{\infty}\frac{ds}{s^3}e^{-m_e^2 s}\left(\frac{abe^2s^2\cos\left[\frac{g}{2}eas\right]\cosh\left[\frac{g}{2}ebs\right]}{\sin[eas]\sinh[ebs]}-1\right)$$

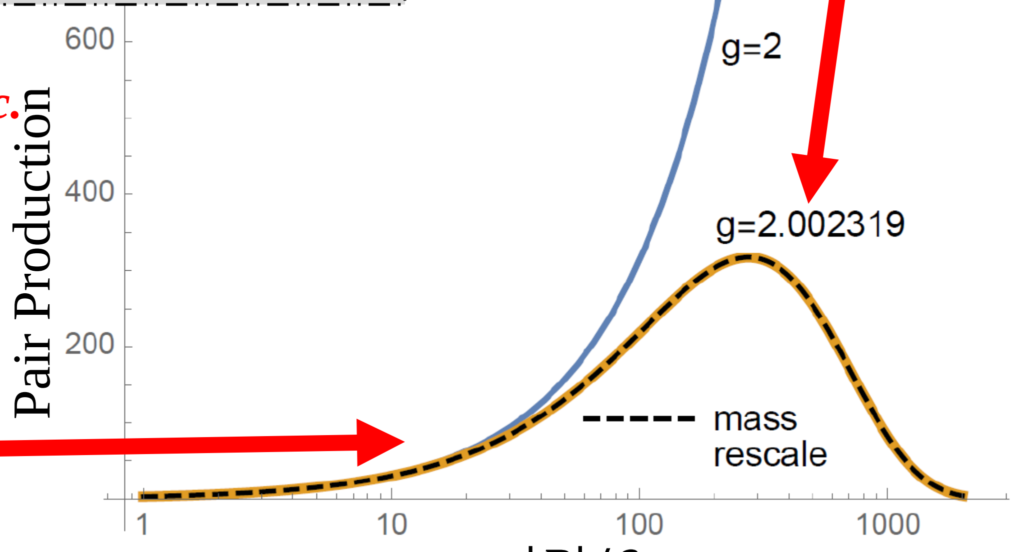
Origin of electron mass? Higgs and electromagnetic.

$$\mathcal{E}_{EHS} = \frac{m_e^2c^3}{e\hbar} = 1.323\times10^{18}\,\frac{\mathrm{V}}{\mathrm{m}}$$

$$a^2 - b^2 = E^2 - B\hat{}2$$
$$a^2b^2 = (E\cdot B)^2$$

$$m_{rescale}^2c^2 = m_e^2c^2 + \left|\frac{g}{2}-1\right|e\hbar B$$

Modification to pair production



$c|\boldsymbol{B}|/\mathcal{E}_{EHS}$

S. Evans and J. Rafelski. “Vacuum stabilized by anomalous magnetic moment.” Phys. Rev. D 98, no.1 016006 (2018)

L. Labun and J. Rafelski, “Acceleration and vacuum temperature.” Phys. Rev. D 86, 041701(R) (2012)

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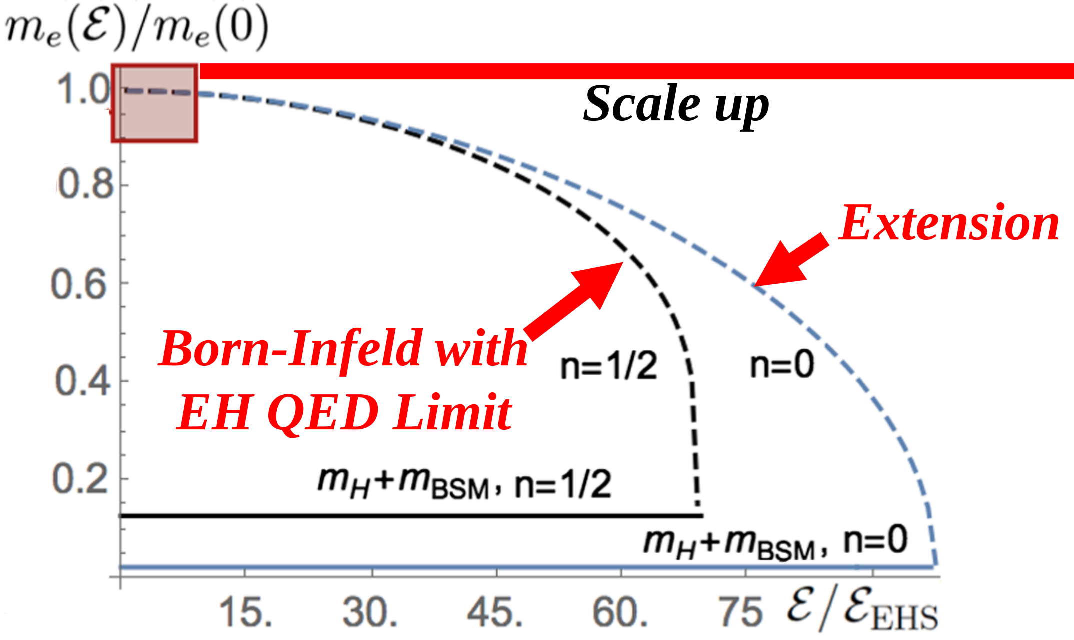
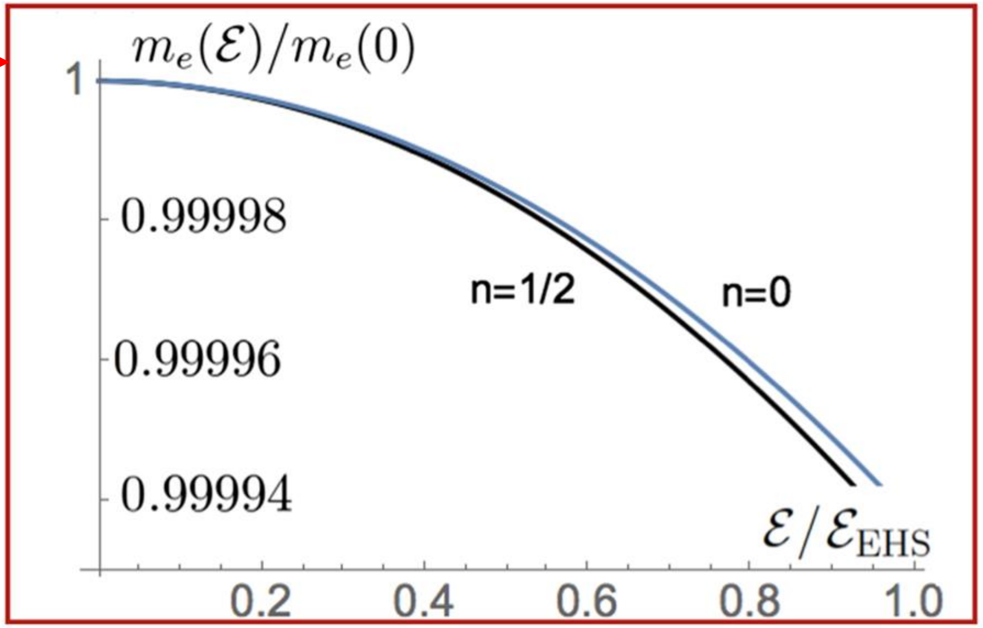
Strong fields probe the origin of electron mass

Origin of mass:

- EM and non-EM (Higgs+BSM) mass components
- EM mass melting in external fields
- Self-consistent feedback with nonlinear EM action

Using Born-Infeld model of the electron.





EM mass content controlled by model parameter $\boldsymbol{n}$

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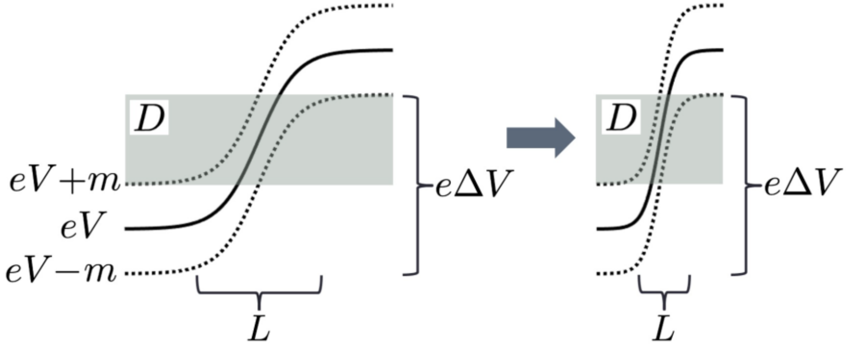
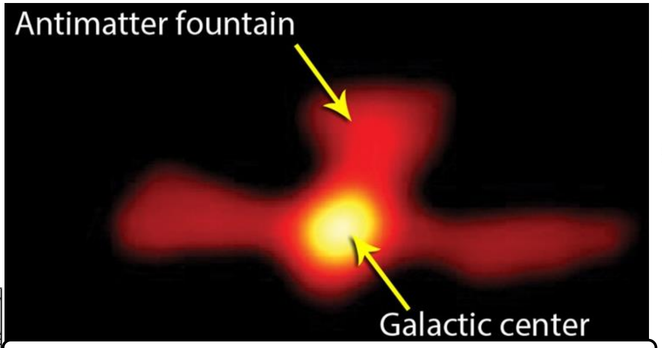
I. Birula. "Nonlinear Electrodynamics: Variations On A Theme By Born And Infeld." In: B. Jancewicz, J. Lukierski: Quantum Theory Of Particles and Fields, World Scientific (1983)

Sauter potential step

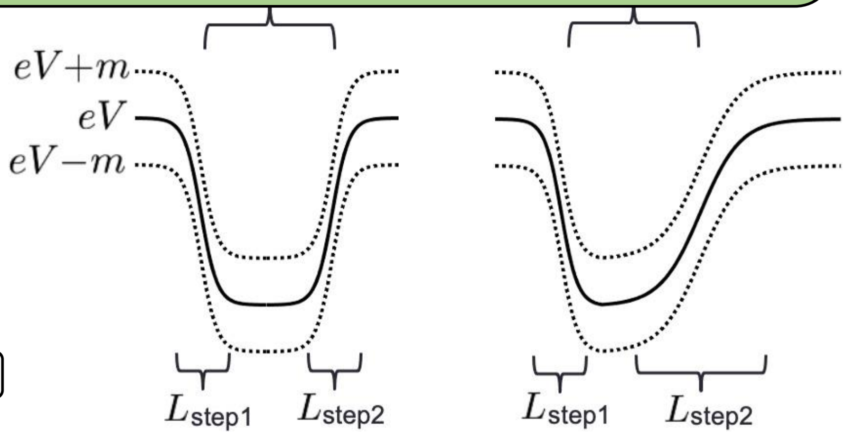
$$V_z = \frac{\mathcal{E}_0 L}{2} \tanh\left[\frac{2z}{L}\right]$$

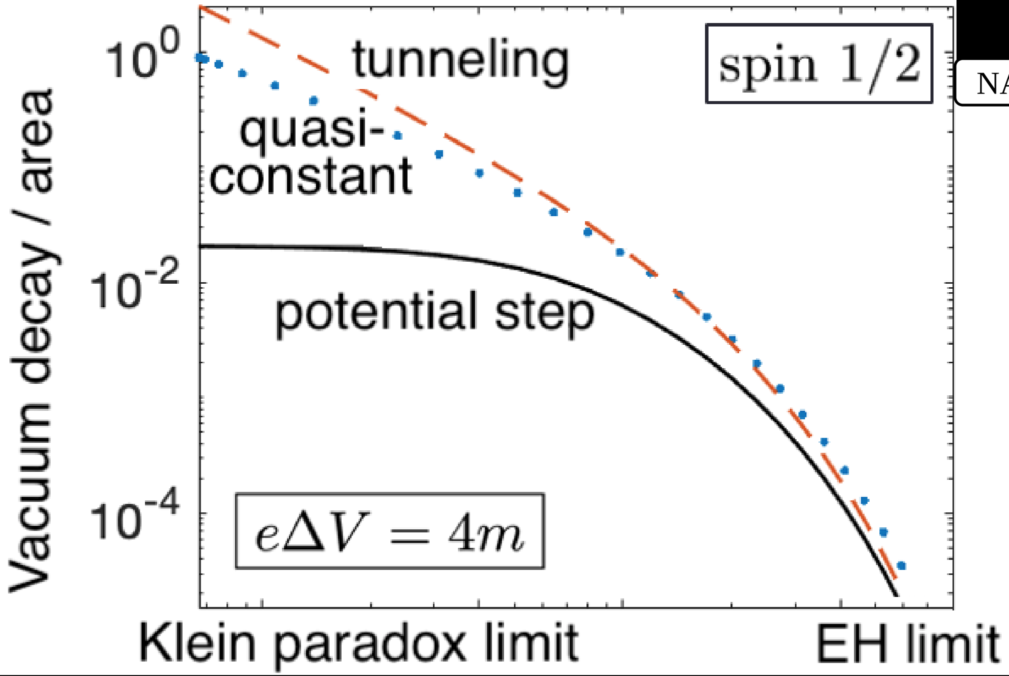
Transition in pair production from Euler-Heisenberg to Klein paradox limit





NASA/W. Purcell, et al. APOD May 1st, 1997.





Step to well

Single potential step or two steps forming a well:

- Finite pair production per unit area versus the diverging rate per volume

Two steps forming a well required for:

- A good definition of vacuum
- Pair production highly sensitive to the shape of the well

Next Slide

As step becomes steep, the forces become very large inducing radiation effects.

S. Evans and J. Rafelski. “Particle production at a finite potential step: Transition from Euler-Heisenberg to Klein paradox.” (2021) [arXiv:2108.12959]

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Completing EM interactions: Covariant classical radiation reaction

$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi m c^3}$$

$$P^{\mu\nu} = g^{\mu\nu} - \frac{u^\mu u^\nu}{u^2}$$

Principle models:

$$m a^\mu = \frac{e}{c} F^{\mu\nu} u_\nu + m\tau_0 \left(\frac{d a^\mu}{d\tau} + \frac{a_\nu a^\nu}{c^2} u^\mu \right)$$

Lorentz-Abraham-Dirac (LAD)

As far as Jackson text goes

$$m a^\mu = \frac{e}{c} F^{\mu\nu} u_\nu + e\tau_0 \left(u \cdot \partial F^{\mu\nu} u_\nu + \frac{e}{m} P^{\mu\nu} F_{\nu\alpha} F^{\alpha\beta} u_\beta \right)$$

Landau-Lifshitz (LL)

As far as LL text goes

$$m a^\mu = \frac{e}{c} F^{\mu\nu} u_\nu + \tau_0 P^\mu_\nu \frac{d}{d\tau} \left(\frac{e}{c} F^{\nu\alpha} u_\alpha \right)$$

Eliezer-Ford-O'Connell (EFO)

The Cinderella of RR?

W. Price, M. Formanek, and J. Rafelski. "Radiation reaction and limiting acceleration". In preparation. (2021)

P. A. M. Dirac, "Classical theory of radiating electrons," Proc. R. Soc. A 167, 148 (1938)

L. D. Landau and E. M. Lifshitz, The Classical Theory of Fields, 2ed, London, England: Pergamon (1962)

S. E. Gralla, A. I. Harte, R. M. Wald. "A Rigorous Derivation of Electromagnetic Self-force." Rev. D80, 024031(2009)

Distinct features of radiation reaction models

LAD

- Requires self-interaction
- Unphysical runaway solutions
- Computationally impossible

Kinematic variables only
$\boldsymbol{a^\mu, \dot{a}^\mu}$

LL

- Equivalent to LAD in perturbative limit
- Useless for strong accelerations

Field variables only
$\boldsymbol{F^{\mu\nu}, \dot{F}^{\mu\nu}}$

EFO

- Maximum limiting acceleration.
- Equivalent to LL for weak acceleration.

Kinematic and Fields
$\boldsymbol{a^\mu, \dot{F}^{\mu\nu}}$

W. Price, M. Formanek, and J. Rafelski. "Radiation reaction and limiting acceleration". In preparation. (2021)
P. A. M. Dirac, "Classical theory of radiating electrons," Proc. R. Soc. A 167, 148 (1938)
L. D. Landau and E. M. Lifshitz, The Classical Theory of Fields, 2ed, London, England: Pergamon (1962)
S. E. Gralla, A. I. Harte, R. M. Wald. "A Rigorous Derivation of Electromagnetic Self-force." Rev. D80, 024031(2009)

Example of limiting acceleration

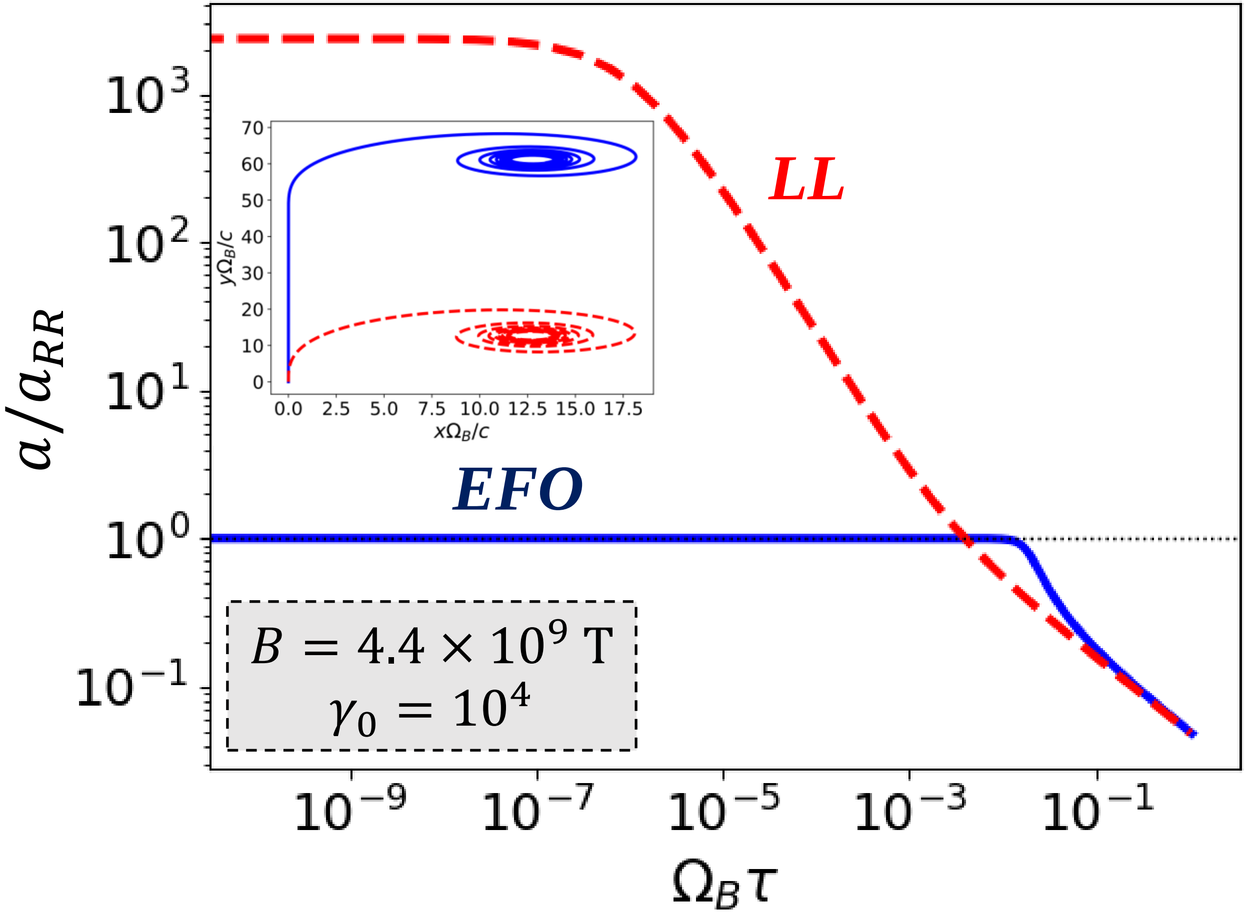
$$\Omega_B = \frac{eB}{m}$$

$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi mc^3}$$

Eliezer-Ford-O'Connell (EFO) in constant magnetic fields

$$a^2 = -\frac{\Omega_B^2\left(c^2(\gamma^2-1)\right)}{1+(\tau_0\Omega_B\gamma)^2}$$

$$\lim_{\gamma\to\infty} a^2 \to -\frac{c^2}{\tau_0^2} \quad \Rightarrow \quad |a_{RR}| = \frac{c}{\tau_0}$$



Limiting acceleration: A common feature with Born-Infeld EM theory

W. Price, M. Formanek, and J. Rafelski. "Radiation reaction and limiting acceleration". In preparation. (2021)

M. Born and L. Infeld. "Foundations of the new field theory." Proc. Roy. Soc. Lond. A 144, no.852, 425 (1934)

I. Birula. "Nonlinear Electrodynamics: Variations On A Theme By Born And Infeld." In: B. Jancewicz, J. Lukierski: Quantum Theory Of Particles and Fields, World Scientific (1983)

Path warping: The new idea for radiation reaction

Start with point external force + Larmor term

$$m\dot{u}^{\mu} = f^{\mu} + m\tau_0 \frac{\dot{u}^2}{c^2} u^{\mu}$$

Omitting problematic Schott term

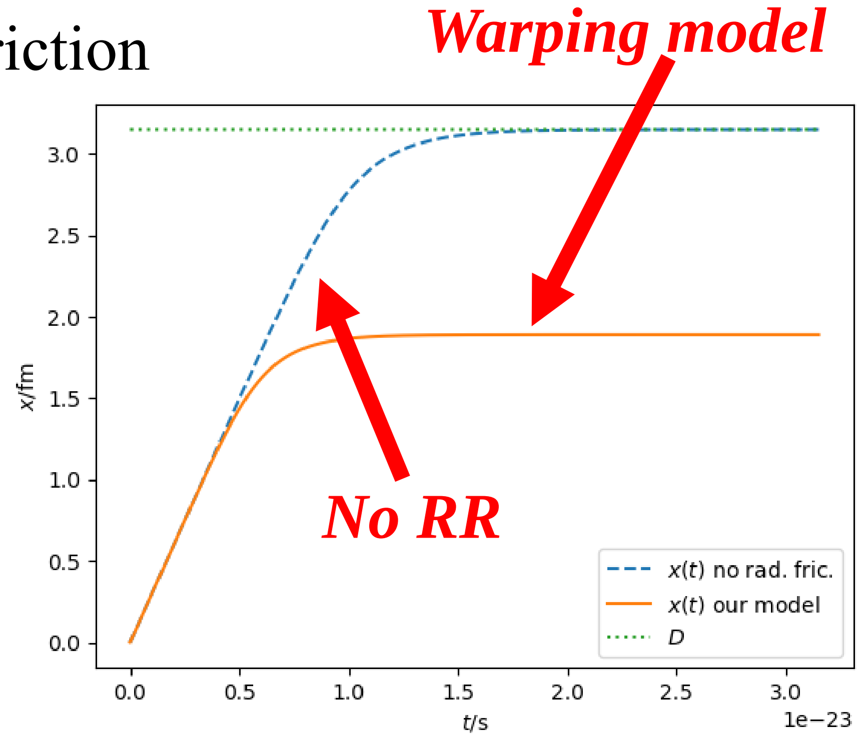
$$m\tau_0 \ddot{u}^{\mu}$$

Introduce "path warping" for particles with medium friction

$$u \cdot \dot{u} = \tau_0 \dot{u}^2 \neq 0 \quad \Leftrightarrow \quad u^2 = w_{\mu\nu} u^{\mu} u^{\nu} = c^2$$

Path warping along world-line of particle

$$u \cdot \dot{u} = -\frac{1}{2}\frac{dw_{\mu\nu}}{d\tau} u^{\mu} u^{\nu} \neq 0$$



Unique particle stopping distance predictions versus other models.

Applications for quark jet quenching in QGP

M. Formanek, A. Steinmetz, and J. Rafelski. "Radiation reaction friction: Resistive material medium." Physical Review D 102.5 (2020): 056015.

Is there a fundamental connection between temperature and acceleration?

Strong Fields → ***Temperature*** ← ***Acceleration***

Interpretation of external fields as temperature

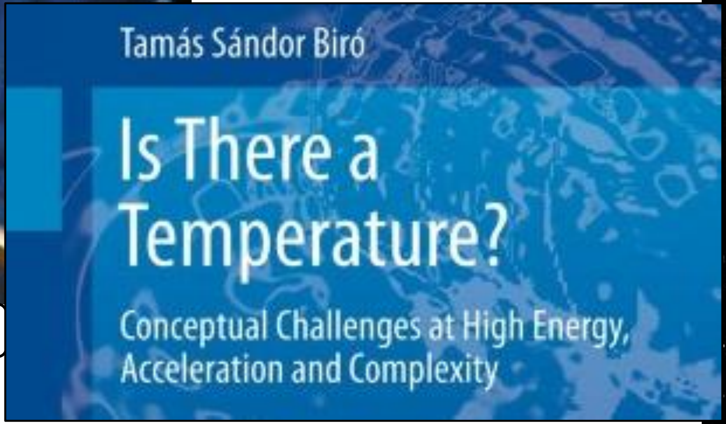
Temperature representation of Euler-Heisenberg action in electric-dominated fields.

Notes on black-hole evaporation

Thermal background (Unruh temperature) experienced by an observer undergoing constant acceleration in a field-free vacuum.

W. H. Unruh

Gravity Swing, Taipei 101, (2012)



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L. Labun and J. Rafelski, "Acceleration and vacuum temperature." Phys. Rev. D 86, 041701(R) (2012)

W-Y. P. Hwang, S. P. Kim, "Vacuum Persistence and Inversion of Spin Statistics in Strong QED." Phys.Rev.D 80 065004 (2009)

(2014 – 2021)

- **Identify challenges in the universe of electromagnetic interactions.**

(2022 – 2030?) Outlook

- **Accomplish understanding of fundamental laws of physics with strong acceleration.**

See presentation by Martin Formanek

See presentation by Chris Grayson

All co-authors available for questions and discussions

Strong Fields: Particles, Plasmas and the Æther Report

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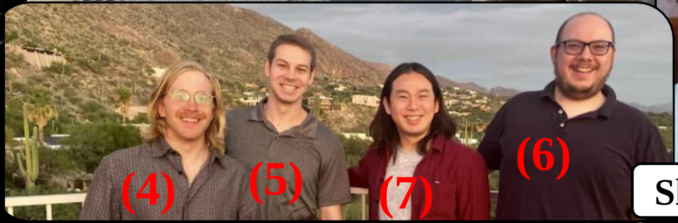
[b] *MPI for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany*

Abstract

We describe recent advances in our understanding of classical and quantum particle dynamics in the presence of strong electromagnetic fields. Strong fields imply strong forces and accelerations in regimes where electrodynamics becomes nonlinear and radiation effects become dominant. The present understanding of the laws of physics was arrived at by observing applied forces in nano-scale regimes as measured in natural units. Therefore, we seek extensions of these laws to fully describe the strong fields physics regime. We explore unit strength acceleration in the experimentally accessible context of ultra-short pulsed lasers, and nonrelativistic and relativistic heavy-ion collisions. We connect individual classical and quantum particle dynamics with high density plasma behavior, and illustrate applications involving atomic, nuclear, and elementary particle physics in the laboratory, in astrophysics and in cosmology. The 'acceleration frontier' is then emerging as a novel research opportunity at the forefront of modern fundamental physics. This is so since acceleration, unlike velocity has an absolute meaning. Exploring strong forces at the acceleration frontier we are probing the structure of Einstein's imponderable æther, today called quantum vacuum.

Keywords: strong fields, critical acceleration, radiation reaction, Euler-Heisenberg, spontaneous particle production, plasma in extreme conditions

Photo by Laszlo Csernai



Slides are a group effort. | Coordinator and creator/artist: Andrew Steinmetz

Supplemental Slide

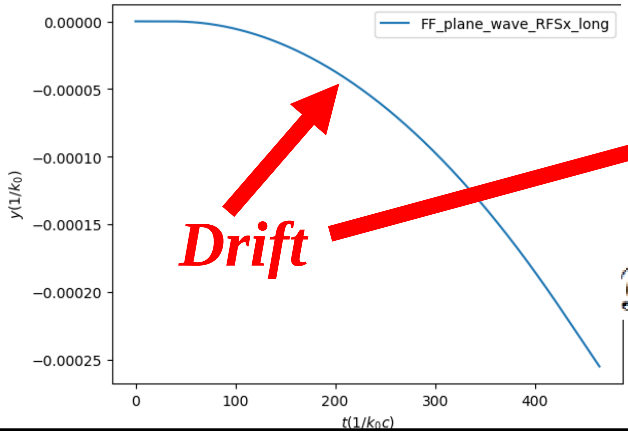
Extended Lorentz force with magnetic dipole: covariant equations are exactly soluble for important examples

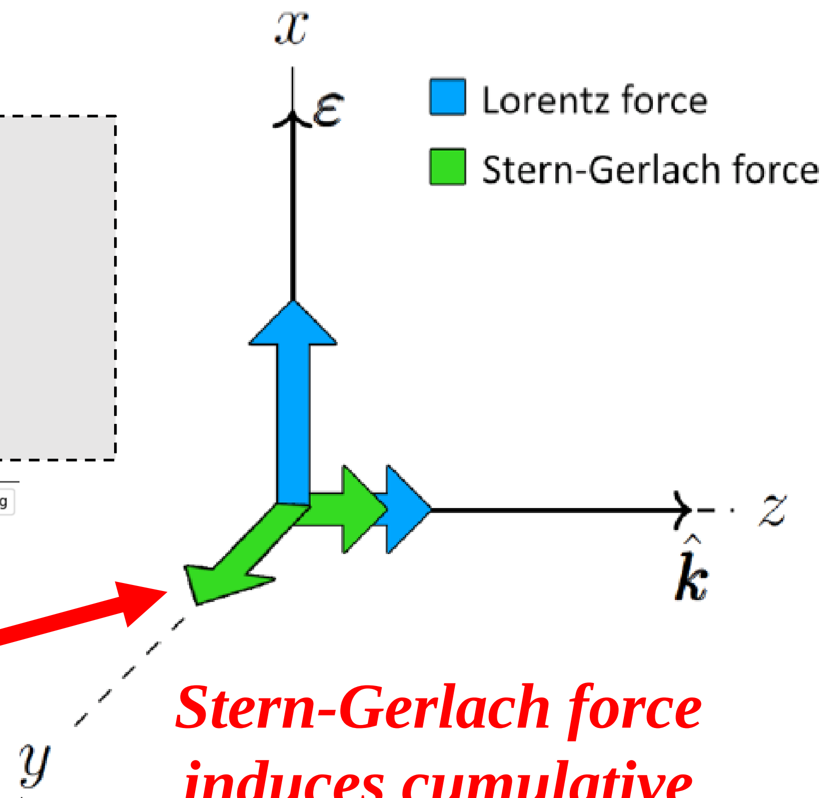
Demonstration of charged solutions for EM plane waves.

$$u^\mu(\tau) = u^\mu(0) - \frac{e}{m}\mathcal{A}_0\psi(\tau)\epsilon^\mu + \frac{1}{2}h^2(\tau)\hat{k}\cdot u(o)\hat{k}^\mu + \frac{e}{m}\frac{\mathcal{A}_0\psi(\tau)}{\hat{k}\cdot u(0)}\left[\epsilon\cdot u(0) + \frac{1}{2}\frac{e}{m}\mathcal{A}_0\psi(\tau)\right]\hat{k}^\mu + h(\tau)\epsilon^{\mu\nu\alpha\beta}u_\nu(0)\hat{k}_\alpha\epsilon_\beta$$

$$h(\tau) \equiv -\frac{d_m\mathcal{A}_0\omega^2}{mc^2}\int_{\tau_0=0}^{\tau}\hat{k}\cdot s(\tilde{\tau})f''(\xi(\tilde{\tau}))d\tilde{\tau}$$

We have also done neutral particles in plane waves.





Stern-Gerlach force induces cumulative off-axis particle drift.

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